

**Photometric study of the star cluster NGC 2155
in the Large Magellanic Cloud: age estimation and variable stars.***M. Otulakowska¹, A. Olech¹, W. Pych¹,
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ABSTRACT

We present results of new photometry for the globular star cluster NGC 2155 in the Large Magellanic Cloud (LMC). Our *I*- and *V*-band observations were obtained with the 6.5-meter Magellan 1 Baade Telescope at Las Campanas Observatory resulting in deep photometry down to $V \sim 24$ mag. By analyzing the color – magnitude diagram for the cluster and utilizing the *Victoria-Regina* grid of isochrones models we estimated the age of the cluster at $\simeq 2.25$ Gyr and $[\text{Fe}/\text{H}] = -0.71$, the numbers which place NGC 2155 outside the age-gap in the age-metallicity relation for LMC clusters. Using the *Difference Image Analysis Package (DIAPL)*, we detected 7 variable stars in the cluster field with variability at the level of 0.01 magnitude in the *I*-band. Three variables are particularly interesting: two SX Phoenixis (SX Phe) stars pulsating in the fundamental mode, and a detached eclipsing binary which is a prime candidate to estimate the distance to the cluster.

Key words: *methods: observational - techniques: photometric - galaxies: individual: LMC - Magellanic Clouds - galaxies: star clusters - stars: distances - stars: variables - globular clusters: individual: NGC 2155 - color-magnitude diagrams*

1. Introduction

The metallicity distribution and star formation history of the Large Magellanic Cloud (LMC) has been the subject of many recent studies, for instance Cole et al.

*This paper includes data gathered with the 6.5 meter Magellan Telescopes located at the Las Campanas Observatory, Chile.

(2009). One of the most intriguing problems is the formation and spatial distribution of the LMC star clusters. This topic was recently studied for example by Beasley, Hoyle, and Sharples (2002) and Baume et al. (2007).

A very peculiar issue about evolution of clusters in this galaxy is the existence of so-called "age gap" in the relation between their age and metallicity. This fact was mentioned for the first time by Jensen, Mould, and Reid (1988), who found that none of LMC clusters has the age between 4 and 10 Gyr. Many further studies were carried out to assign the properties of the "age gap", for instance Geisler et al. (1997) studied 25 LMC clusters and found no cluster formation during the period 3-8 Gyr ago. They reported the cluster formation to start again about 3 Gyr ago with a peak at about 1.5 Gyr ago. Sarajedini (1998) discovered three star clusters with the age of about 4 Gyr, thus in the "age gap", among them NGC 2155. Following studies showed these ages were perhaps overestimated, for example Kerber, Santiago, and Brocato (2007), and the series of three publications based on the VLT data: Gallart et al. (2003), Woo et al. (2003), Bertelli et al. (2003). The most recent determinations show the range of the "age-gap" to be about 3 - 10 Gyrs, see Balbinot et al. (2010). The corresponding metallicity gap, which is less discussed in the literature, is also very evident for the LMC clusters. It ranges from $[\text{Fe}/\text{H}] \approx -0.7$, for younger LMC clusters, to $[\text{Fe}/\text{H}] \approx -2.0$ for older ones, see Olszewski et al. (1991). Nevertheless, the problem of the "age gap" in the age-metallicity relation for LMC clusters still remains unsolved. The NGC 2155 cluster is one of the candidates to fit in the gap. In this contribution we report our estimate of the age of NGC 2155. We also address the matter of variable stars in the field of NGC 2155; currently none has been known.

The paper is arranged as follows. In section 2. we give information on the observations and data reduction. Color-Magnitude Diagram for the NGC 2155 is presented in section 2.2. In section 3. we describe isochrones fitting and age estimation for the cluster. Section 4. is dedicated to variable stars which we found in the field of NGC 2155. In section 5. we discuss the most interesting variables we found, two SX Phe stars. We summarize the conclusions of this work in section 6.

2. Observations and data reduction

We conducted photometric observations of the star cluster NGC 2155 in the Large Magellanic Cloud (LMC) on four nights between 07 December 2002 and 11 December 2002. We used the TEK#5 CCD camera attached to the Baade 6.5 m telescope (Magellan 1) at the Las Campanas Observatory, Chile. The field of view was 2.36×2.36 arcminutes with the scale 0.069 arcsec/pixel. The Johnson-Cousins *B*, *V* and *I* passband filters were used. The exposure times for *B* were set at 300 and 600 seconds while the exposure times for *V* and *I* were set at 300 seconds.

On the night of 07/08 December 2002, due to poor weather conditions, we managed to obtain only 11 images of NGC2155 in *I* and 3 images in *V*. These

images suffered from poor seeing and have not been used in our analysis. On the night of 08/09 December 2002, we obtained 48 images in *I*, 12 images in *V* and 2 images in *B*; we have selected only 14 frames in *I* for further analysis. On the night of 09/10 December 2002, we obtained 50 images in *I*, 14 images in *V* and 3 images in *B*; we have selected 45 frames in *I* and 8 frames in *V* for further analysis. Finally, on the night of 10/11 December 2002, we obtained 55 images in *I*, 11 images in *V* and 1 image in *B* of which, for further processing we used 47 frames in *I* and 9 frames in *V*. A summary of the number of used frames is given in the Table 2. For the used 106 frames in *I* and 17 frames in *V*, the median seeing was 0.88 arcsec and 0.94 arcsec (FWHM), respectively.

Table 1: Log of observations of NGC 2155 for the nights 7/8 – 10/11 Dec 2002

Filter	Exposure time [sec]	Number of obtained frames	Number of selected frames	Median seeing of selected frames [arcsec]
<i>B</i>	600.0	6	0	-
<i>V</i>	300.0	40	17	0.94
<i>I</i>	300.0	164	106	0.88

Bias subtraction and flat-field correction of the images were done using the standard procedures within *IRAF*¹ *noao.imred.ccdred* package. We have used programs from the *DIAPL*² and *DAOPHOT* (Stetson 1987) packages to perform image subtraction and photometry.

Using *DIAPL*, we created the "template" images of the NGC 2155 from the best 10 frames in *I* and 8 frames in *V*. They are shown in the Fig 1. The figure clearly shows the very highly compact nature of the cluster.

The standard routines of the software package *DIAPL* allowed us to detect variable stars based on the data from only the two last nights of observations which had the acceptable weather conditions. The package operates through subtraction of a template frame from each of the obtained frames. The output from *DIAPL* was a set of files with photometry in arbitrary analog counts. After that, we converted the light curves from counts to instrumental magnitudes, and later on to standard magnitudes as described below.

Stellar profile photometry was performed using the *DAOPHOT/ALLSTAR* routines of *DAOPHOT*, see Stetson (1987). The PSF model for every frame was obtained from a set of unsaturated and isolated stars. We extracted instrumental photometry for all 2715 stars in the template list.

In the Fig. 2, we present *rms* errors as a function of instrumental magnitude for the both template images. Positions of the red clump in these plots at the instrumental magnitudes $i \approx 11.5$ and $v \approx 12$ are clearly visible.

¹IRAF is distributed by the National Optical Astronomical Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science

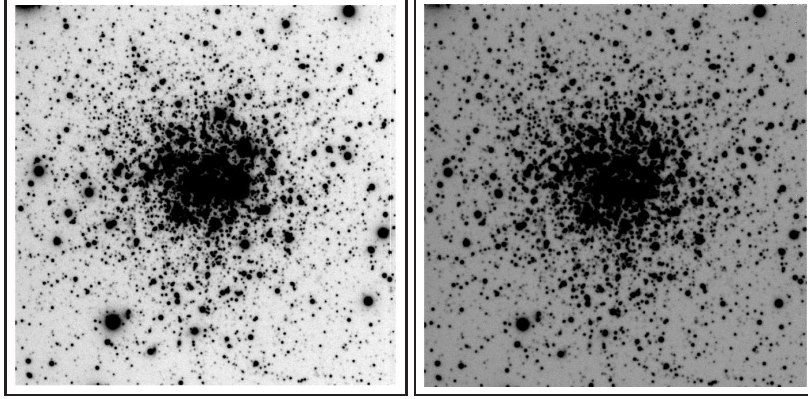


Figure 1: Our "template" images obtained from *DIAPL* package. Left: *I*-band, right: *V*-band.

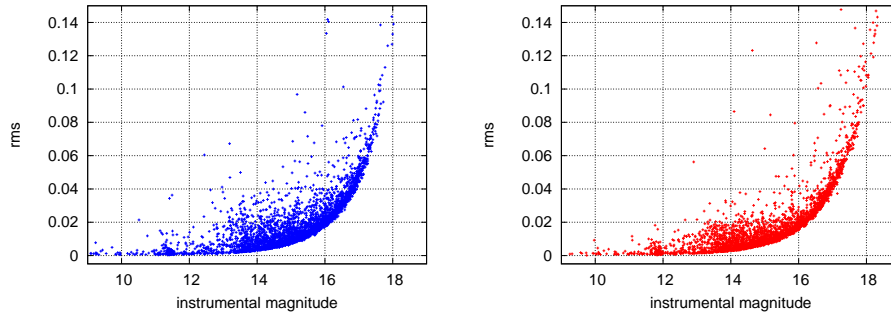


Figure 2: A test of the photometry quality: the relation between instrumental magnitude and its *rms* deviation obtained from *ALLSTAR*. Left: results for the *I*-band, right: results for the *V*-band.

2.1. Calibration

The following equations were used to transform our data to the magnitude system of the previous observations of the cluster by Zaritsky et al. (2004):

$$I - i = \alpha_1 + \beta_1(v - i) \quad (1)$$

$$V - v = \alpha_2 + \beta_2(v - i) \quad (2)$$

where I, V refer to standard system values, and i, v are our instrumental magnitudes.

We found: $\alpha_1 = 6.320 \pm 0.017$, $\beta_1 = 0.213 \pm 0.028$, $\alpha_2 = 6.819 \pm 0.014$ and $\beta_2 = 0.272 \pm 0.023$.

2.2. Color-Magnitude Diagrams (CMD)

We compared our CMD (before extinction corrections) with the CMD based on the data of Zaritsky et al. (2004), which has been used as standard magnitudes in our calibration procedure. The diagrams are shown in the Fig. 3. The comparison confirms that our calibration to standard magnitudes went fine: we can see the location of the red clump of our CMD is in the same place as in the data of Zaritsky et al. (2004), although our photometry appears to be by far more accurate.

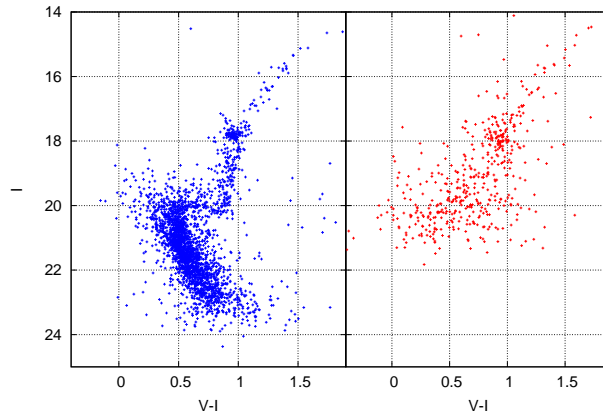


Figure 3: CMD comparison. Left: our CMD, right: CMD of Zaritsky et al. (2004).

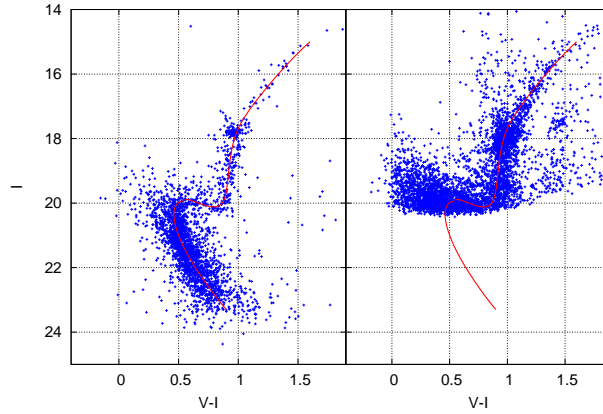


Figure 4: CMD comparison. Left: our CMD, right: CMD of Udalski (1998).

Another test of our transformations was a comparison with the data of Udalski-

ski (1998), as shown in Fig. 4. We added a curve representing the trend of our data points to both panels of the figure to facilitate the comparison. Again, the results are in agreement and what is more, we can clearly see how much deeper our CMD is. This gives us a chance to successfully determine the age and metallicity of the cluster from the location of its Main Sequence.

2.3. Extinction correction

Originally we intended to apply position-dependent extinction corrections within the field of the cluster, so we divided the field into a mosaic of subfields, as shown in the Fig. 5. We made tests for such a grid of 3×3 to 5×5 , each time calculating the average value of extinction for every subfield using values derived with the online tool *Reddening Estimator for the LMC* by Zaritsky et al. (2004)³.

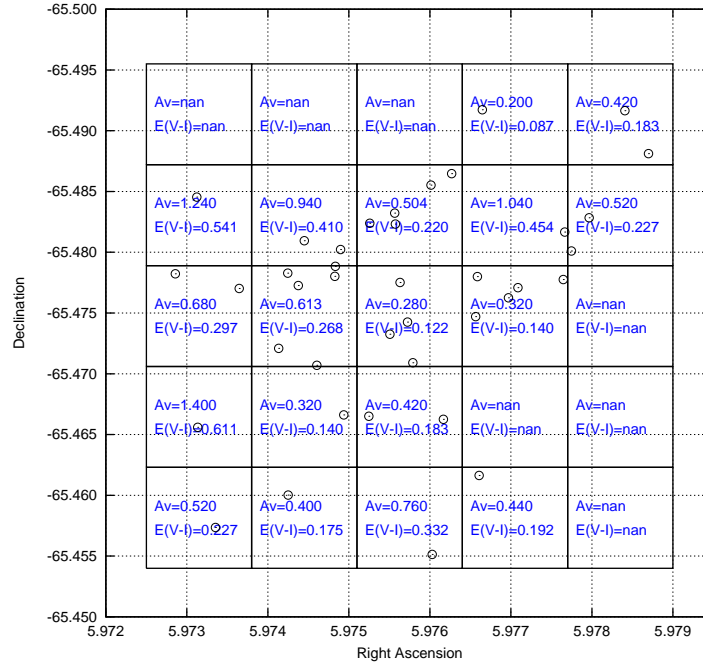


Figure 5: An example map of averaged values of interstellar extinction for each subfield. Dots represent data points from Zaritsky et al. (2004). "nan" stands for "Not a Number" which is a result for subfields with no data points.

However, during this process we realized that this procedure leads to too few stars per sub-field to make this kind of statistics reasonable. Thus, we decided to use the mean value of extinction for the whole field 2.5×2.5 [arcmin], which is the

³<http://ngala.as.arizona.edu/dennis/lmcext.html>

mean value calculated using *all stars model* (hot and cool stars) of Zaritsky et al. (2004): $\langle A_V \rangle = 0.56$, centered on right ascension $\alpha = 5.97567$ [h] and declination $\delta = -65.47722$ [°].

Following Schlegel, Finkbeiner, and Davis (1998) we assumed:

$$\frac{A_V}{E(B - V)} = 3.315$$

$$\frac{A_I}{E(B - V)} = 1.940$$

leading to:

$$\frac{A_V}{E(V - I)} = 2.410$$

3. Age estimate for NGC 2155

There have been several attempts to estimate the age of NGC 2155; the most recent are listed in the Tab. 2. The results differ because of variety of combinations of the used parameters and isochrone models. The range of the derived ages is 2.3 to 3.6 Gyr, with most estimates falling within 2.5 – 3.0 Gyr.

To estimate the age of NGC 2155 based on our CMD, we used the isochrones called *The Victoria-Regina Stellar Models* from VandenBerg, Bergbusch, and Dowler (2006). From the grid of evolutionary tracks we chose the one which is closest to our CMD in its shape. We tried a wide range of metallicities and ages with, and without, the convective-core overshooting. We found the best isochrone for our CMD is the one with the metallicity of $[\text{Fe}/\text{H}] = -0.71$, age 2.25 Gyr, and with the overshooting.

There are a few parameters which have an influence on the shape of isochrones. They are the main sources of uncertainties while estimating the age of a star cluster. Especially assumptions on the distance to the cluster and the chosen metallicity are the reasons for cluster age differences between the studies.

For the bolometric correction we applied the values from Bessell, Castelli, and Plez (1998), and for the interstellar reddening the values from Schlegel, Finkbeiner, and Davis (1998). For the value of the distance modulus to the LMC, we have chosen $m - M = 18.50 \pm 0.13$, following Benedict et al. (2002). We used studies from the Tab. 2. and references in there to find the range of metallicity for NGC 2155. Considering this data we fitted isochrones of each metallicity possible to find the best one (Fig. 6). A very influential parameter for the estimate of the age of the cluster is the convective core overshooting. As was shown for instance by Woo et al. (2003), it has a great impact on the shape of the CMD and must be provided for intermediate-age star clusters. The effect of the existence of binaries and field stars on the CMD has a minor influence on the age estimate and is difficult to calculate. Thus, we do not consider it in our study, as was also done in most of prior studies.

Table 2: Recent age estimations for LMC star cluster NGC 2155. Z is the mass fraction abundances of all elements heavier than helium. Standard errors are given when available. Isochrones names are clarified in the given references.

theoretical isochrone name	distance modulus ($m - M$) _V	filters used	metallicity [Fe/H]	Z	obtained age [Gyr]	source
Girardi		B, V	-0.68		3.2	^a
Geneva	18.55 ± 0.10	C, T_1	-0.9 ± 0.2	0.004	3.6 ± 0.7	^b
Yonsei-Yale	18.5	V, R	-0.7	0.004	3.0	^c
Padova	18.5	V, R	-0.7	0.004	2.5	^c
Padova		V, R		0.003	2.8	^d
Yonsei-Yale	18.5	V, R		0.004	2.7	^e
Yonsei-Yale	18.5	V, R		0.004	2.9	^e
Victoria-Regina	18.65	V, R	-0.83		2.3	^f
-	18.32 ± 0.04	B, V	-0.7 ± 0.1	0.004 ± 0.001	3.0 ± 0.25	^g
Victoria-Regina	18.5	V, I	-0.71		2.25	^h

^a Rich, Shara and Zurek (2001)

^b Piatti et al. (2002)

^c Gallart et al. (2003)

^d Bertelli et al. (2003)

^e Woo et al. (2003)

^f VandenBerg, Bergbusch, and Dowler (2006)

^g Kerber, Santiago, and Brocato (2007)

^h This work

Although taking into consideration the binary fraction could improve the fitting of isochrones along the main sequence.

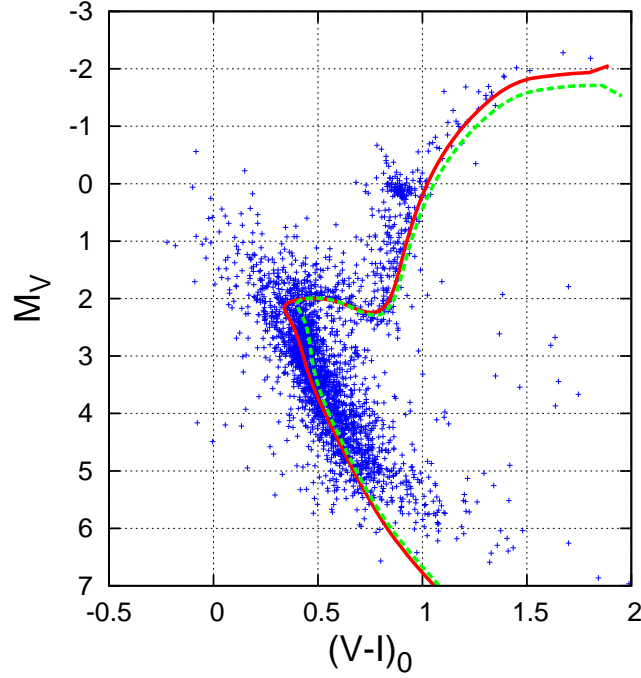


Figure 6: Our best isochrones fitting: two isochrones of the metallicity $[\text{Fe}/\text{H}] = -0.71$ (green dashed curve) and $[\text{Fe}/\text{H}] = -0.83$ (red solid curve), the age of 2.25 Gyr, and with convective core overshooting, are plotted on our CMD. See description in text.

In the Fig. 6, the green (dashed) curve gives our best isochrone fitting to the CMD of NGC 2155. The choice of the best isochrone is quite ambiguous, though. In this figure we can see a comparison of two isochrones with the age of 2.25 Gyr of metallicity $[\text{Fe}/\text{H}] = -0.71$ (the green dashed curve) and $[\text{Fe}/\text{H}] = -0.83$ (the red solid one). Along the main-sequence (MS) the green curve fits the CMD better than the red one: it is located in the very center of the MS, whereas the red curve is shifted to the left. The opposite situation appears on the upper part of the CMD: the trend of our CMD is better represented by the red curve. However, we need to remember that we used a grid of isochrones, thus the real metallicity of NGC 2155 could be somewhere in between these two values, which are represented by the lines. Some higher metallicity would improve the fit of the red giant branch (RGB) but then the rest of the slope would not be fitted by this model.

4. Variable stars

The results of our search for short-period variable stars are given in the Tab. 3. To find variability we used the Optimal Image Subtraction method, see Alard and Lupton (1998) and Alard (2000), implemented by Wozniak (2000) and Wojtek Pych⁴.

We analyzed results of the image subtraction for data from only the two best nights. We were able to detect a few dozen variability events but with such a small amount of data we could not verify most of them. Thus, we report here only the most probable variables, see Tab. 3.

Table 3: Coordinates and light curve parameters for variable stars of NGC 2155. Periods are given in days. A_I is the amplitude of the light curve in the I -band.

Name	α	δ	$\langle V \rangle$	$\langle V-I \rangle$	A_I	Period	Type
NGC2155-V1	5.975308	-65.467840	20.27	0.24	0.37	0.05977	SX Phe
NGC2155-V2	5.975305	-65.479066	19.39	0.21	0.51	0.08949	SX Phe
NGC2155-V3	5.976201	-65.474401	19.41	0.46	0.40	1.36083	Ecl. binary
NGC2155-V4	5.976681	-65.463650	20.61	1.09	0.26	4.83398	LP
NGC2155-V5	5.978492	-65.471589	18.02	1.21	0.06	0.71841	Red giant
NGC2155-V6	5.973289	-65.470010	17.69	1.26	0.03	0.34361	Red giant
NGC2155-V7	5.976252	-65.476893	16.98	1.39	0.04	0.37629	Red giant

We discovered seven new periodic variables. We were not aware of any previously known variable in NGC 2155. The periods were obtained with the method of Schwarzenberg-Czerny (1996). The CMD for NGC 2155 with positions of variables is shown in the Fig. 7 and the phased light curves of these stars are given in the Fig. 8.

The first two variables, **NGC2155-V1** and **NGC2155-V2**, can be securely classified as SX Phe stars. The short periods of 0.059771 and 0.089495 days, the trends of their light curves and positions on the CMD in the blue stragglers region are a clear argument for the SX Phe assignment. We claim that these stars are pulsating in the fundamental mode, because of their asymmetric light curves and very large amplitudes. The argument that SX Phe stars with large amplitudes are pulsating in the fundamental mode, and those with $\Delta V \leq 0.2$ mag in the first overtone was presented for example by Rodríguez and López-González (2000) and Santolamazza et al. (2001). Since these stars are more interesting than the remaining variables, we dedicate a separate Section 5. to them.

The third variable, **NGC2155-V3**, is a beautiful example of a detached eclipsing binary star. The period given here (1.360828 days) is plausible but not a certain one because we did not detect the second eclipse with our short time interval data. This star is an attractive target for future observations because such a detached binary can be used to determine the distance to the cluster and to the LMC.

⁴<http://users.camk.edu.pl/pych/DIAPL/>

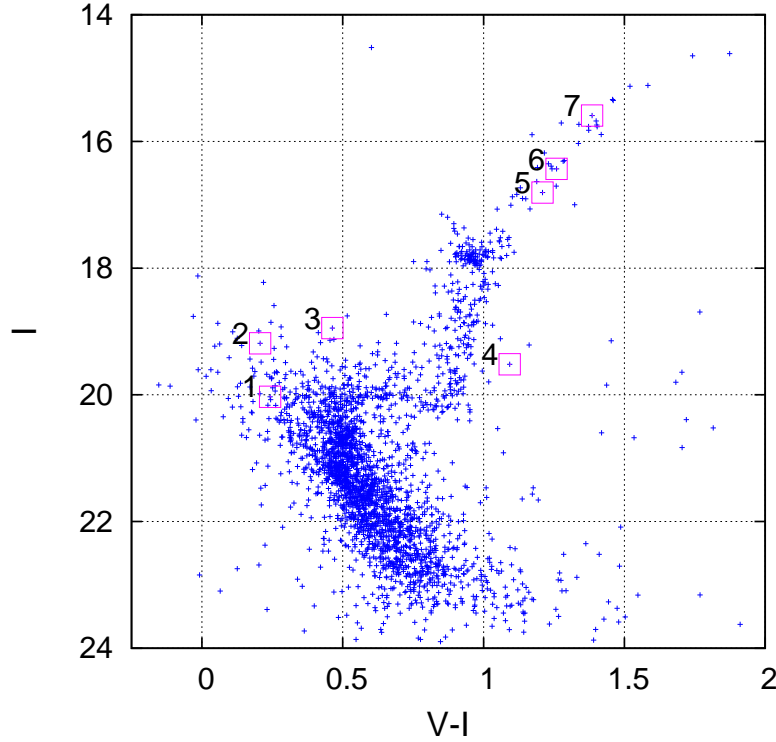


Figure 7: The color-magnitude diagram of NGC2155 with marked positions of our variables. Numbers correspond to the last letter of a variable's name given in the Tab.3

NGC2155-V4 is a long period (LP) subgiant star. The light curve here reveals only its variability; again, the period of 4.833980 days is uncertain. The position of NGC2155-V4 on the CMD confirms that this is a LP-type star.

The three remaining variable stars, **NGC2155-V5**, **NGC2155-V6** and **NGC2155-V7**, are classified as red giants, based on their location on the CMD. Their variability is most likely connected with pulsations or/and chromospheric activity.

5. SX Phe variables

5.1. Distance moduli from period-luminosity relations

SX Phe variables are pulsating stars of Population II, very similar to δ Scuti stars which are objects of Population I. Taking into account relatively large distance and crowding in the observed field we can detect only one or two radial modes excited at short periods of \sim hours. In globular clusters SX Phe stars are most often found in the blue stragglers stars (BSS) region of the CMD. These objects are very interesting because their evolution cannot be explained with the standard theory for

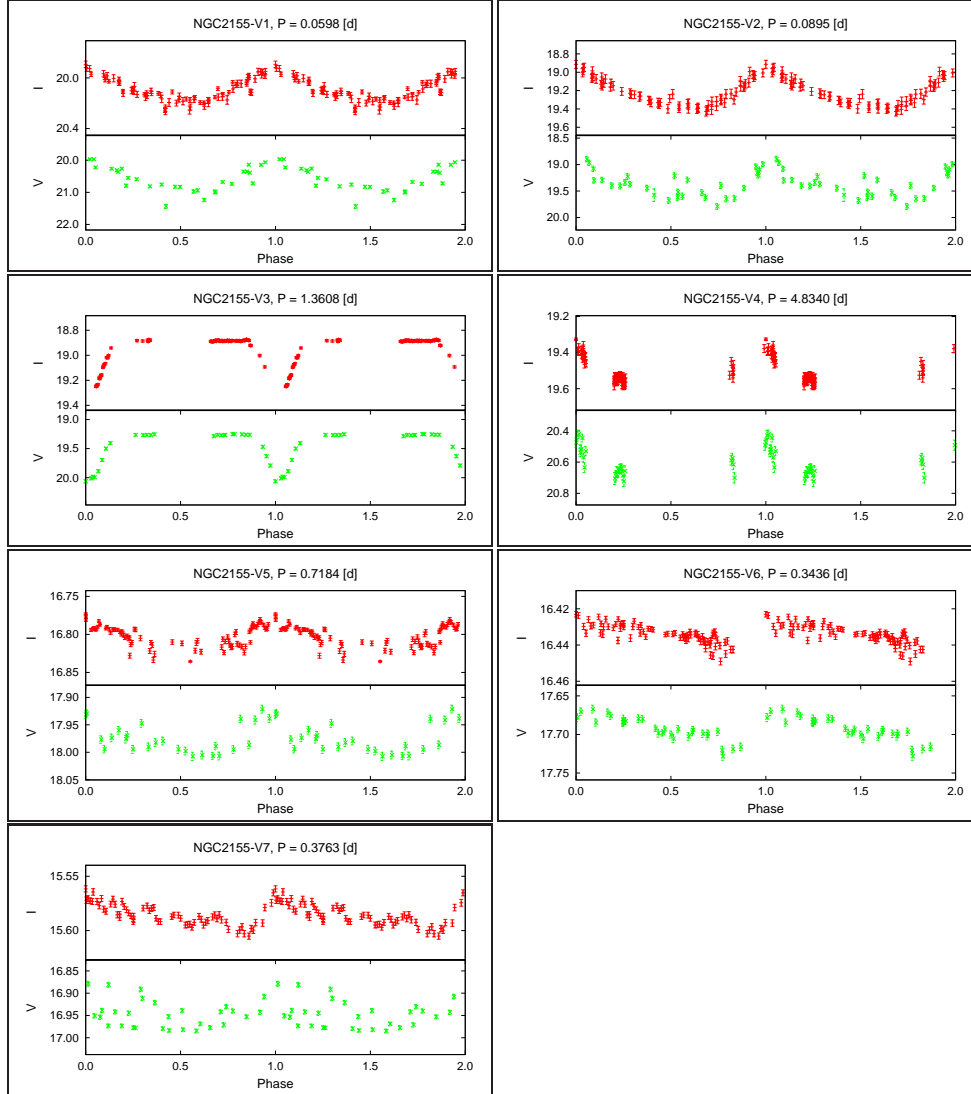


Figure 8: Phased light curves for our newly discovered NGC 2155 variables.

a single star. BSS were the subject of many studies and debates and nowadays it is believed that they are products of mergers of MS stars or binaries in dense star clusters. Their existence has an important influence on the evolution of the whole system, as has been shown for instance by Lombardi and Rasio (2002).

In this context the globular cluster NGC 2155 is interesting for at least two reasons. First, it consists of a significant population of BSS as can be seen in our Fig. 6. Second, there are two SX Phe variables (the detected here NGC2155-V1 and NGC2155-V2) located in the blue straggler region of the cluster. If these two variables are real members of the cluster, their pulsational properties might give strong constraints on the physical parameters of the cluster itself. One should remember

that, compared to the Galactic globular clusters, the NGC 2155 is relatively young. Thus its turn-off point and blue stragglers are much bluer than in clusters in our Galaxy. A quick comparison with globular cluster of similar metallicity, 47 Tuc, which age is estimated to around 11.25 Gyr (Thompson et al. 2010), shows that the turn-off point of NGC 2155 is about 0.3 mag bluer (see $V/V - I$ CMD of 47 Tuc in Rosenberg et al. 2000). This might suggest that SX Phe stars in NGC 2155 are located outside of the classical pulsation instability strip and their basic properties (chemical composition?) are different than in Galactic SX Phe stars.

For our SX Phe new detections we can derive the distance. Such stars pulsating in the fundamental mode can be used as "standard candles" (see references in the Tab. 4). We know the periods of these objects; from absolute magnitude - period relations we can compute the absolute magnitudes of our SX Phe stars (see Tab. 4), and from them, the distance modulus. However, it is challenging to compute it for a longer period SX Phe, because most of the $M_V - P$ relations are derived from stars with short periods. What is more, $M_V - P$ relations depend strongly on the selection criteria of the stars which were used to derive these relations. It is sometimes challenging to identify the mode of SX Phe star securely, this leads to a wrong classification of SX Phe stars, which causes high uncertainties in these relations.

Due to the fact that NGC2155-V1 and NGC2155-V2 have slightly asymmetric light curves and relatively large peak-to-peak amplitudes of variability, we believe that both stars pulsate in the fundamental mode. Thus, we can use the known period-luminosity relations to determine their absolute magnitudes and the distance modulus. Yet, following Gilliland et al. (1998), we present several period-luminosity (P-L) relations for BSS which have been published in recent years and we apply them to our data (Tab. 4).

The P-L relation has the following form:

$$M_V = A \cdot \log P + B$$

where A and B are constants determined from a set of observed periods (P) and absolute magnitudes (M_V) for a sample of stars.

The distance moduli for both our SX Phe variables appear to indicate that they are foreground stars located in the halo of our Galaxy or perhaps in remnants of tidal streams of LMC, but not in the cluster. On the other hand, probability that two SX Phe stars are located exactly half-way between us and LMC and are additionally placed in the BSS region of NGC 2155 must be exceedingly low. This would be an extraordinary coincidence. Thus, in our opinion, these stars may belong to the cluster but their physical properties may be different than in typical SX Phe stars in the Galaxy. We will discuss it in details in the subsection 5.2.

In the literature, unsuccessful cases of application of P-L relation have been described before. For instance, Gilliland et al. (1998) found that for SX Phe

Table 4: Parameters of NGC 2155 V1 and V2 based on various period - absolute magnitude calibrations.

A	B	M_{V1}	M_{V2}	$(m - M_{V1})_V$	$(m - M_{V2})_V$	reference
-2.56	0.13	3.26	2.81	16.84	16.41	Nemec, Nemec, and Lutz (1994)
-3.29	-1.16	2.86	2.29	17.24	16.94	D. H. McNamara (1995)
-3.74	-1.91	2.66	2.01	17.44	17.21	Hog and Petersen (1997)
-2.90	-1.20	2.35	1.84	17.75	17.38	Fernie (1992)
-3.05	-1.32	2.41	1.88	17.69	17.35	Santolamazza et al. (2001)
-3.65	-1.38	3.08	2.45	17.02	16.78	Poretti et al. (2008)
-3.725	-1.933	2.62	1.97	17.48	17.25	D. McNamara (1997)
-2.88	-0.77	2.75	2.25	17.35	16.98	Pych et al. (2001)

stars in 47 Tuc the observed magnitudes are brighter than calculated from these relations. This discrepancy can be caused by the metallicity of these clusters. NGC 2155 and 47 Tuc have approximately the same metallicity: $[\text{Fe}/\text{H}] \approx -0.71$ and $[\text{Fe}/\text{H}] \approx -0.83$ (VandenBerg 2000). Several authors have already shown that the pulsation properties of SX Phe stars are affected by their metal content, for example D. McNamara (1997), Rodríguez and López-González (2000) and Santolamazza et al. (2001). The studies show that the periods of SX Phe variables are larger for the clusters which have a higher metallicity.

The problem of P-L relations application for NGC2155-V1 and NGC2155-V2 is evident. There is of course some uncertainty which comes from these relations, but the discrepancy in our case is extremely high. To check whether we deal with some peculiar stars we decided to make further and more detailed study.

5.2. Observations vs. theory

All the calibrations up to obtaining absolute magnitudes M_V and colors were already done and described in the Sect. 2. They are valid for stars in the field of NGC 2155. However, if we want to compare the observations with models we need to estimate effective temperatures (T_{eff}) and luminosities (L), i.e. bolometric corrections, for our two SX Phe stars. This was done based on Kurucz model atmospheres used in Bessell, Castelli, and Plez 1998 work. The resulting values are as follows (errors in luminosity come from the error of distance modulus of NGC 2155):

Object	$\log T_{\text{eff}}$	$\log L$
NGC2155-V1	3.9039 ± 0.0474	1.242 ± 0.052
NGC2155-V2	3.9125 ± 0.0456	1.598 ± 0.052

Fig. 9 shows theoretical main sequence with a few evolutionary tracks for selected masses, also with the ZAMS and TAMS (dotted lines). Thick solid line marks the blue edge of pulsational instability for radial fundamental mode. Along

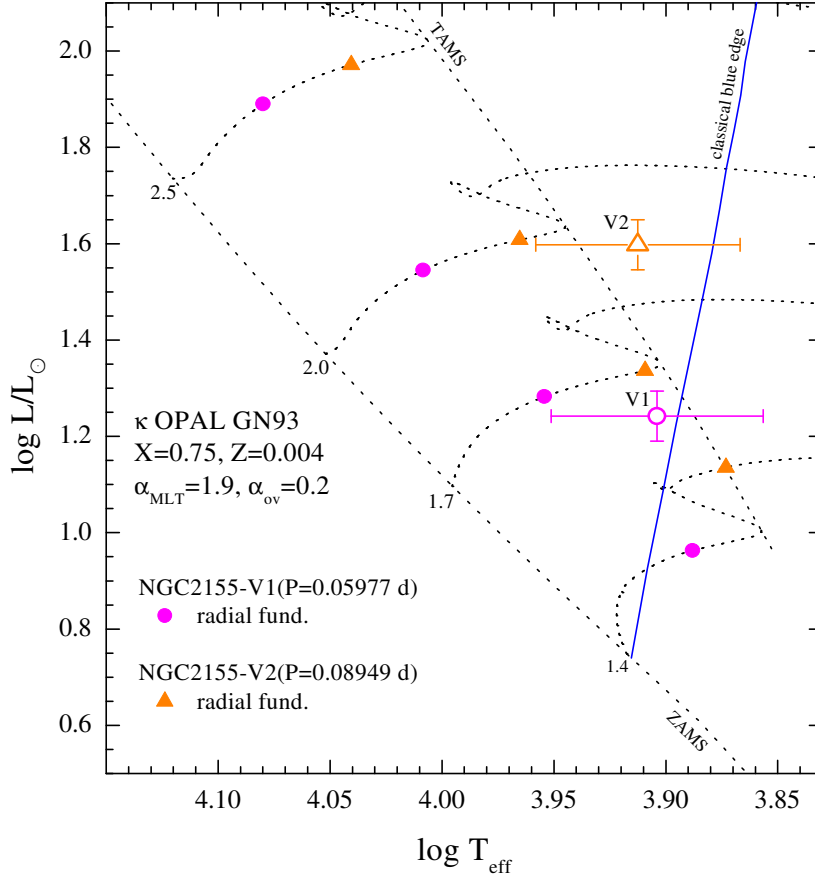


Figure 9: The observed positions of our two SX Phe stars, NGC2155-V1 and NGC2155-V2, on the HR diagram, plotted with the theoretical main sequence of a few evolutionary tracks for selected masses, which are calculated with the Warsaw-New Jersey code. See details in the text.

the selected evolutionary tracks models with fixed periods of radial fundamental mode are marked: 0.05977 days (filled circles) and 0.08949 days (filled triangles) which correspond to observed periods of variables NGC2155-V1 and NGC2155-V2, respectively. The observed positions of both variables are shown with their error crosses.

Evolutionary calculations were performed with the Warsaw-New Jersey code using the OPAL opacities (Iglesias and Rogers 1996) and assuming solar proportions in abundances of chemical elements heavier than helium according to Grevesse and Noels (1993). The computations were performed for the hydrogen mass fraction $X = 0.75$ and heavy element mass fraction (metallicity) $Z = 0.004$. Such a choice of chemical composition was caused by the requirement to achieve

agreement with the best fit isochrone. In stellar envelope, the standard mixing-length theory of convection with the mixing-length parameter $\alpha(MLT) = 1.9$ (solar-like) was used. For overshooting a two-parameter description was used (Dziembowski and Pamyatnykh 2008) with the choice of parameters which corresponds approximately to usual one-parameter description with $\alpha(\nu) = 0.2$.

Linear nonadiabatic analysis of the radial oscillations was performed using a code developed by W. A. Dziembowski (for general description see Dziembowski 1977).

It can be seen very clearly that the observed periods do not fit the theoretical values for standard evolutionary models. Moreover, the stars at positions of observed variables in the HR diagram must not be pulsating - they are located left to the blue edge of instability region.

To solve both these problems (fitting the periods as those of the radial fundamental mode, and ensuring the pulsational instability of this mode), the theoretical models must be changed both in global stellar mass and chemical composition. To fit periods, masses of both variables must be significantly higher than those of standard evolutionary models. To ensure the instability, it is necessary to increase the helium abundance in the models (pulsations in the classical instability strip are driven mainly in the second helium ionization zone in the stellar envelope, so the higher helium abundance results in a widening of the instability region in the HR diagram).

The preliminary tests show that it is possible to fit periods and achieve instability at the positions of variables in the HR diagram if their stellar masses are by factor 1.8 – 2.3 larger than evolutionary values (for NGC2155-V1, the required mass is $2.95 M_{\odot}$, 1.8 times larger of the evolutionary value $1.6 M_{\odot}$; for NGC2155-V2, the required mass is $4.1 M_{\odot}$, 2.1 – 2.3 times larger of the evolutionary value 1.8 – $1.9 M_{\odot}$). To ensure instability for radial fundamental mode, the helium mass fraction, Y , must be of about 0.40 – 0.45 instead of the standard value of about 0.25 ($Y = 1 - X - Z$). Potentially, such helium-rich stars can be produced during evolution of close binary systems as result of very effective mass transfer or merger of the components (we note the paper of Fedorova, Tutukov, and Yungelson (2004), especially Figs. 3 and 4 there, which may argue in favor of such a hypothesis). We plan to study this hypothesis in more detail.

6. Summary

Using the 6.5m Magellan-1 telescope we obtained a Color-Magnitude Diagram for NGC 2155 which is the deepest one in I and V bands ever published for this cluster. Our analysis showed that the age of NGC 2155 is 2.25 Gyr which is even one of the lowest values found for this cluster. Therefore we confirm the location of this cluster outside the age gap of LMC star clusters. NGC 2155 seems to be among the very first clusters formed after the gap, so its age is critical to deter-

mine the lower limit of the age gap. We found the metallicity of NGC 2155 is $[\text{Fe}/\text{H}] = -0.71$, which is in agreement with previous studies for this cluster.

An interesting results of our study is the discovery of seven variable stars. Among them, three deserve a special attention. First, the detached binary star (NGC2155-V3) which should be considered as a target for future studies, because this object could allow us to compute the accurate distance to the NGC 2155. Next, two SX Phe stars (NGC2155-V1 and NGC2155-V2) pulsating in the fundamental mode, with very peculiar behaviour, namely long periods (0.05977 and 0.08949 d, respectively) which seem to be in disagreement with known P-L relations for BSS. They cannot be explained by standard evolutionary models and need a further investigation.

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REFERENCES

- Alard, C. 2000, *A&AS*, **144**, 363-370.
 Alard, C. and Lupton, R. H. 1998, *ApJ*, **503**, 325-+.
 Balbinot, E. et al. 2010, *MNRAS*, **404**, 1625-1632.
 Baume, G. et al. 2007, *MNRAS*, **375**, 1077-1086.
 Beasley, M. A. and Hoyle, F. and Sharples, R. M. 2002, *MNRAS*, **336**, 168-188.
 Benedict, G. F. et al. 2002, *AJ*, **124**, 1695-1705.
 Bertelli, G. et al. 2003, *AJ*, **125**, 770-784.
 Bessell, M. S. and Castelli, F. and Plez, B. 1998, *A&A*, **333**, 231-250.
 Cole, A. A. et al. 2009, *Proc Int Astron Union*, **256**, 263-268.
 Dziembowski, W. 1977, *Acta Astronomica*, **27**, 95-126.
 Dziembowski, W. A. and Pamyatnykh, A. A. 2008, *MNRAS*, **385**, 2061-2068.
 Fedorova, A. V. and Tutukov, A. V. and Yungelson, L. R. 2004, *AL*, **30**, 73-85.
 Fernie, J. D. 1992, *AJ*, **103**, 1647-1651.
 Gallart, C. et al. 2003, *AJ*, **125**, 742-753.
 Geisler, D. et al. 1997, *AJ*, **114**, 1920-+.
 Gilliland, R. L. et al. 1998, *ApJ*, **507**, 818-845.
 Grevesse, N. and Noels, A. 1993, *Symposium in Honour of Hubert Reeves' 60th birthday*, **jan**, 15-25.
 Hog, E. and Petersen, J. O. 1997, *A&A*, **323**, 827-830.
 Igelesias, C. A. and Rogers, F. J. 1996, *ApJ*, **464**, 943-+.
 Jensen, J. and Mould, J. and Reid, N. 1988, *ApJS*, **67**, 77-83.
 Kerber, L. O. and Santiago, B. X. and Brocato, E. 2007, *A&A*, **462**, 139-156.

- Lombardi, Jr., J. C. et al. 2002, *ASPCS*, **263**, 35-+.
- McNamara, D. 1997, *PASP*, **109**, 1221-1232.
- McNamara, D. H. 1995, *AJ*, **109**, 1751-1756.
- Nemec, J. M. and Nemec, A. F. L. and Lutz, T. E. 1994, *AJ*, **108**, 222-246.
- Olszewski, E. W. and Schommer, R. A. and Suntzeff, N. B. and Harris, H. C. 1991, *AJ*, **101**, 515-537.
- Piatti, A. E. et al. 2002, *MNRAS*, **329**, 556-566.
- Poretti, E. et al. 2008, *ApJ*, **685**, 947-957.
- Pych, W. et al. 2001, *A&A*, **367**, 148-158.
- Rich, R. M. and Shara, M. M. and Zurek, D. 2001, *AJ*, **122**, 842-848.
- Rodríguez, E. and López-González, M. J. 2000, *A&A*, **359**, 597-600.
- Rosenberg, A. and Piotto, G. and Saviane, I. and Aparicio, A. 2000, *A&AS*, **144**, 5-38.
- Santolamazza, P. et al. 2001, *ApJ*, **554**, 1124-1140.
- Sarajedini, A. 1998, *arXiv:astro-ph/9804340v1*, , .
- Schlegel, D. J. and Finkbeiner, D. P. and Davis, M. 1998, *ApJ*, **500**, 525.
- Schwarzenberg-Czerny, A. 1996, *ApJL*, **460**, L107+.
- Stetson, P. B. 1987, *PASP*, **99**, 191-222.
- Thompson, I. B. et al. 2010, *AJ*, **139**, 329-341.
- Udalski, A. 1998, *Acta Astronomica*, **48**, 383-404.
- VandenBerg, D. A. 2000, *ApJS*, **129**, 315-352.
- VandenBerg, D. A. and Bergbusch, P. A. and Dowler, P. D. 2006, *ApJS*, **162**, 375-387.
- Woo, J.-H. and Gallart, C. and Demarque, P. and Yi, S. and Zoccali, M. 2003, *AJ*, **125**, 754-769.
- Wozniak, P. R. 2000, *Acta Astronomica*, **50**, 421-450.
- Zaritsky, D. and Harris, J. and Thompson, I. B. and Grebel, E. K. 2004, *AJ*, **128**, 1606-1614.